The "Ridge" in Proton-Proton Scattering at 7 TeV

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One of the most important experimental results for proton-proton scattering at the LHC is the observation of a so-called "ridge" structure in the two particle correlation function versus the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$. One finds a strong correlation around $\Delta\phi = 0$, extended over many units in $\Delta\eta$. We show that a hydrodynamical expansion based on flux tube initial conditions leads in a natural way to the observed structure. To get this result, we have to perform an event-by-event calculation, because the effect is due to statistical fluctuations of the initial conditions, together with a subsequent collective expansion. This is a strong point in favour of a fluid-like behavior even in *pp* scattering, where we have to deal with length scales of the order of 0.1 fm.

The CMS collaboration published recently results [1] on two particle correlations in $\Delta\eta$ and $\Delta\phi$, in *pp* scattering at 7 TeV. Most remarkable is the discovery of a ridge-like structure around $\Delta\phi = 0$, extended over many units in $\Delta\eta$, referred to as "the ridge", in high multiplicity *pp* events. A similar structure has been observed in heavy ion collisions at RHIC, and there is little doubt that the phenomenon is related to the hydrodynamical evolution of matter [2–5]. This "fluid dynamical behavior" is actually considered to be the major discovery at RHIC mainly based on the studies of azimuthal anisotropies [6–10].

So does *pp* scattering provide as well a liquid, just ten times smaller than a heavy ion collision? It seems so! We showed recently [11] that if we take exactly the same hydrodynamic approach which has been so successful for heavy ion collisions at RHIC [12], and apply it to *pp* scattering, we obtain already very encouraging results compared to *pp* data at 0.9 TeV. In this paper, we apply this fluid approach, always the same procedure, to understand the 7 TeV results. Before discussing the details of the approach, we present the most important results of this work, namely the correlation function. In fig. 1, we show that our hydrodynamic picture indeed leads to a near-side ridge, around $\Delta\phi = 0$, extended over many units in $\Delta\eta$. In fig. 2, we show in the corresponding result for the pure basic string model, without hydro evolution. There is no ridge any more! This shows that the hydrodynamical evolution "makes" the effect. One should note that the correlation functions are defined and normalized as in the CMS publication, so we can say that our "ridge"

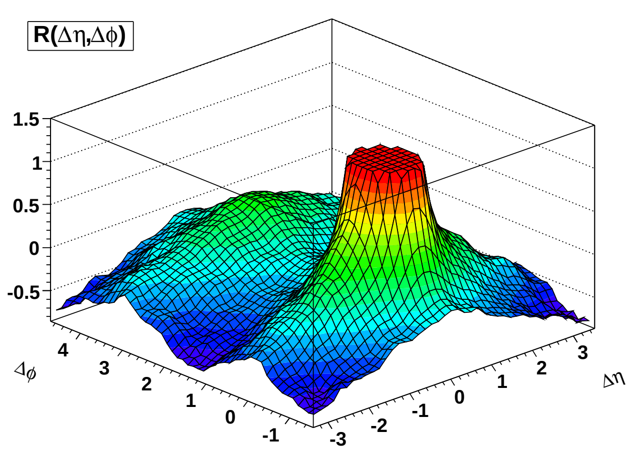

Figure **1**: (Color online) Two particle correlation function R versus $\Delta\eta$ and $\Delta\phi$ for high multiplicity events in *pp* collisions at 7 TeV, as obtained from a hydrodynamical evolution based on flux tube initial conditions. We consider particles with p_t between 1 and 3 GeV/c.

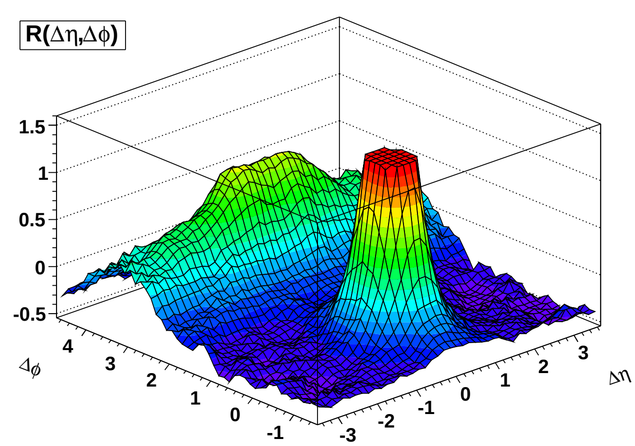

Figure **2**: (Color online) Same as figure 1, but calculation without hydro evolution .i.e. particle production directly from string (flux tube) decay.

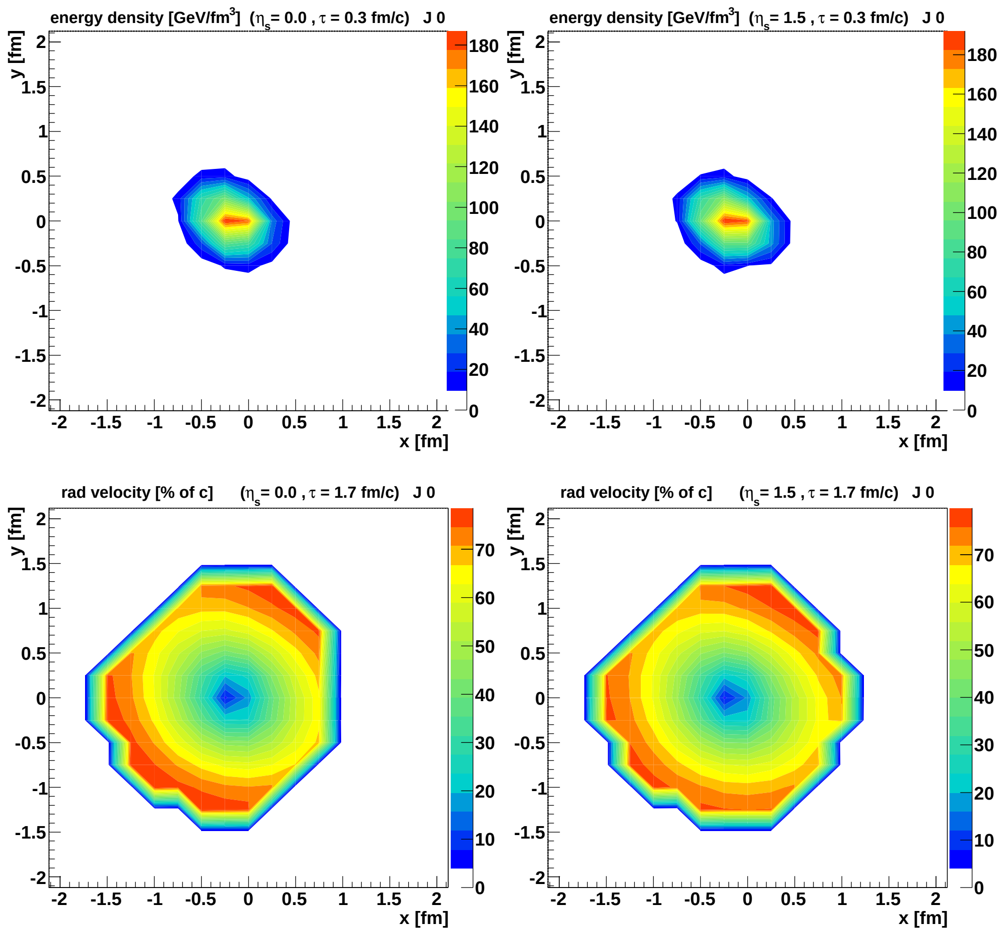

Figure **3**: (Color online) Initial energy density (upper panel) and radial flow velocity at a later time (lower panel) for a high multiplicity *pp* collision at 7 TeV at a space-time rapidity $\eta_s = 0$ (left) and $\eta_s = 1.5$ (right).

is quite close in shape and in magnitude compared the experimental result. The experimental high multiplicity bin corresponds to about 7 times average, whereas in our calculation (extremely demanding concerning CPU power) "high multiplicity" refers to 5.3 times average (we actually trigger on events with 10 elementary scatterings). We cannot go beyond at the moment.

It is easy to understand the origin of the ridge, in a hydrodynamical approach based on flux tube initial conditions. Imagine many (say 20) flux tubes of small transverse size (radius ≈ 0.2 fm), but very long (many units of space-time rapidity η_s). For a given event, their transverse positions are randomly distributed within the overlap area of the two protons. Even for zero impact parameter (which dominated for high multiplicity events), this randomness produces azimuthal asymmetries, as shown in fig. 3, upper panel. The energy density obtained from the overlapping flux tubes (details will be discussed later) shows an elliptical shape. And since the flux tubes are long, and only the transverse positions are random, we observe the same asymmetry at different longitudinal positions ($\eta = 0$ and $\eta = 1.5$ in the figure). So we observe a translational invariant azimuthal asymmetry!

If one takes this asymmetric but translational invariant energy density as initial condition for a hydrodynamical evolution, the translational invariance is conserved, and in particular translated into other quantities, like the flow. In fig. 3, lower panel, we show the radial flow velocity at a later time again at the two space-time rapidities $\eta_s = 0$ (left) and $\eta_s = 1.5$ (right). In both cases, the flow is more developed along the direction perpendicular to the principal axis of the initial energy density ellipse. This is a very typical fluid dynamical phenomenon, referred to as elliptical flow.

Finally, particles are produced from the flowing liquid, with a preference in the direction of large flow. This preferred direction is therefore the same at different values of η_s. And since η_s and pseudorapidity η are highly corre-

lated, one observes a $\Delta\eta\Delta\phi$ correlation, around $\Delta\eta = 0$, extended over many units in $\Delta\eta$: a particle emitted a some pseudorapidity η has a large chance to see a second particle at any pseudorapidity to be emitted in the same azimuthal direction.

Here, a couple of remarks are in order. It should be mentioned that the magnitude of the radial flow (and all observables affected by this flow) are depending on the choice of the flux tube radius. A bigger radius leads to smaller flow. The value of 0.2 fm has been chosen to get an overall best picture for all observables depending on flow. In our picture, the ridge effect is biggest at intermediate values of p_t, because at lower p_t the effect from flow on the particle p_t is small (flow can only increase p_t), whereas at large p_t the effect has to disappear because particles are coming from jets rather than the fragmenting fluid. Finally we have to admit that – although the ridge seems to be reproduced in form a magnitude – the awayside ridge is too low in the simulation. The problem with the awayside region is the fact that here the cut between core and corona is crucial. In a first version we allowed all string segments with p_t larger than 3 GeV/c to escape from the core, with the result of having almost no awayside correlation, because all candidates were included in the core plasma. So we were forced to reduce this cutoff to 1 GeV/c, which gives some awayside ridge without destroying the p_t spectra. In reality there is of course no cutoff but "some continuous procedure", but this is a project for the future. It should also be mentioned that momentum conservation contributes to the correlation, as discussed in [13], and the usual hadronization procedure in hydrodynamical calculations (Cooper-Frye) does not conserve momentum event-by-event. However, this should not modify the form of the near-side ridge. In fig. 2, we show a calculation with perfect momentum conservation, and the effect on the near-side is indeed a reduction of the correlation function (negative values), but its form is a plateau, not a valley.

In our approach the elliptical flow plays an important role, as discussed earlier. This is perfectly compatible with a recent analysis [13], where the ridge correlation is obtained from a elliptical parametrization of particle spectra. The are a couple of publications discussing elliptical flow in *pp*. Closest to our approach is the work presented in [14], where the eccentricity ϵ in *pp* scattering is obtained from statistical fluctuations, as in our model. The elliptical flow v_2 is then obtained simply from an empirical v_2/ϵ relation. In refs. [15, 16], an initial eccentricity ϵ is obtained from a Glauber type model similar to the one employed for heavy ion collisions, which leads to elliptical flow using 2D hydrodynamics [15] or an empirical v_2/ϵ relation [16]. The Glauber picture is quite different to ours, where the main origin of asymmetry are statistical fluctuations, not geometry. Finally, also in [17], elliptical flow is obtained in a hydrodynamical calculation, but here based on parametrized initial conditions. We obtain a numerical value for the integrated v_2 of about 0.01 at midrapidity, compatibel with values of about 0.05 at intermediate pt from other calculations

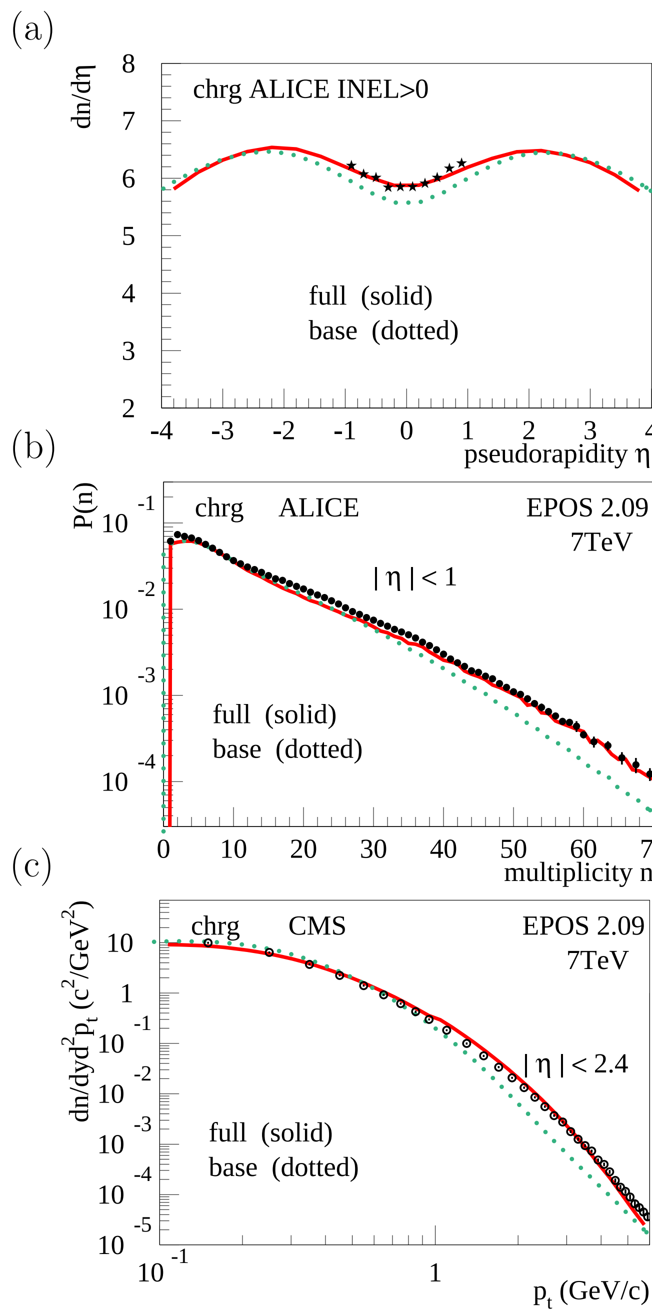

Figure **4**: (Color online) Pseudorapidity distribution (INEL>0 trigger) (a), multiplicity distribution (b), and transverse momentum distribution (c) in *pp* scattering at 7 TeV, compared to data (points). We show the full calculation (solid line), and a calculation without hydrodynamic evolution (dotted).

[13, 19].

Elliptical flow is an important issue, but crucial for the discussion in this paper is, however, the fact that the (elliptical) asymmetry of the flow is translational invariant, coming from the flux tube structure. So the main point of this paper is not the elliptical flow itself, but the fact that it is translational invariant, which leads to the long range structure. Another important issue is the randomness of the initial conditions. To treat all these elements in a realistic calculation, we present here for the first time an even-by-event treatment (see also [12, 18]) of the 3+1 dimensional hydrodynamical evolution for *pp* scattering, based on random initial conditions. This is an enormous computational effort. A *pp* calculation is as demanding as a heavy ion scattering: the volume is smaller, but the cell sizes as well. On the other hand the multiplicities in *pp* are small, so in particular for correlation studies a very large number of events has to be simulated. Triggering is much more difficult in *pp* compared to *AA*, because in *pp* multiplicity and geometrical centrality are much less correlated than in *AA*.

Our hydrodynamical approach gives "a natural explanation" of the ridge phenomenon, without any need to construct asymmetries by hand. This is a strong point in favor of a collective fluid-like behavior of matter even in *pp* scattering, which is still considered by many people as an "elementary interaction".

The "flux tube + hydro" approach has been extensively discussed in [11, 12]. Crucial is an event-by-event treatment of the hydrodynamic evolution (3D treatment, realistic equation of state), where the initial condition for each event is obtained from an EPOS 2 calculation. This is a multiple scattering approach, providing multiple "parton ladders", which are identified with elementary flux tubes [21], the latter ones treated as classical strings. In case of very high energy proton-proton collisions, in particular for large numbers of scatterings, in a large fraction of the volume the density of strings will be so high that they cannot possibly decay independently. Instead, based on the four-momenta of infinitesimal string segments, one computes the energy density $\varepsilon(\tau_0, \vec{x})$ (see fig. 3) and the flow velocity $\vec{v}(\tau_0, \vec{x})$, which serve as initial conditions for the subsequent hydrodynamic evolution, which lets the system expand and cool down till freeze out at some T_H according to the Cooper-Frye prescription.

Our above-mentioned results concerning the ridge are only meaningful if the model can reproduce elementary distributions. In the following we will compare two different scenarios: the full calculations, including hydro evolution (full), and a calculation without hydrodynamical evolution (base). In fig. 4(a), we show pseudorapidity distributions of charged particles, compared to data from ALICE [22] . The two scenarios do not differ very much, and agree roughly with the data. Also the multiplicity distribution agrees reasonably well with data, see fig. 4(b). We then investigate transverse momentum distributions in fig. 4(c). Here the base calculation (without hydro) underestimates the data at intermediate p_t by a large factor, whereas the full calculation gets close to the data. This is a very typical behavior of collective flow: the distributions get harder at intermediate values of p_t (around 1-5 GeV/c).

Experimentally, the ridge correlation is only observed for high multiplicity events, and the effect is biggest for intermediate values of p_t (1-3 GeV/c), and disappears towards large and small values. Why is this so? We recall that also in pp the core-corona procedure is very important: only regions with strongly overlapping strings contribute to the core (and are treated via hydrodynamics), and this overlap is more likely to happen in high multiplicity events. As a consequence of the reduced hydro-contribution, the difference between the full calculation and the "no hydro" version is relatively small in low multiplicity events (with multiplicities close to or smaller than minimum bias), and therefore "collective effects" like elliptical flow or this ridge correlations will disappear with decreasing multiplicity. The role of the transverse momenta can be seen from fig. 4(c). The main "flow effect" appears at intermediate values of p_t (1-3 GeV/c), as can be seen from the difference between the full calculation and the one without hydro: particle production from a transversely flowing liquid will produce preferentially intermediate p_t particles. At large p_t, there will be no effect, since these particles originate from hard prcesses, not from the liquid.

To summarize: our hydrodynamic approach based on flux tube initial conditions, which has already been applied to explain very successfully hundreds of of spectra in AuAu collisions at RHIC, and which excellently describes the so-far published LHC spectra and Bose-Einstein correlation functions, provides in a natural fashion a so-called near-side ridge correlation in $\Delta\eta$ and $\Delta\phi$. This structure appears as a consequence of a longitudinal invariant asymmetry of the energy density from overlapping flux tubes, which translates into longitudinal invariant elliptical flow.

[1] CMS Collaboration, JHEP 1009:091,2010
[2] STAR Collaboration: J. Adams, et al, Nucl. Phys. A757:102, 2005
[3] PHENIX Collaboration, K. Adcox, et al, Nucl. Phys. A757:184-283, 2005
[4] BRAHMS Collaboration, I. Arsene et al., Nucl. Phys. A757:1-27, 2005
[5] PHOBOS Collaboration, B.B. Back et al., Nucl. Phys.

A757:28-101, 2005
[6] P. Huovinen, in Quark-Gluon Plasma 3, eds. R. C. Hwa and X. N. Wang (World Scientific, Singapore, 2004)
[7] P. F. Kolb and U. Heinz, in Quark-Gluon Plasma 3, eds. R. C. Hwa and X. N. Wang (World Scientific, Singapore, 2004)
[8] U. W. Heinz and P. F. Kolb, Nucl. Phys. A 702 (2002) 269
[9] P. Huovinen, P. F. Kolb, U. W. Heinz, P. V. Ruuskanen and S. A. Voloshin, Phys. Lett. B 503 (2001) 58
[10] U. W. Heinz, P. F. Kolb, Nucl. Phys. A702:269 (2002)
[11] K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, arXiv:1010.0400, to be published in Phys. Rev. C
[12] K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, Phys. Rev. C 82, 044904 (2010)
[13] P. Bozek, arXiv:1010.0405
[14] J. Casalderrey-Solana, U. A. Wiedemann, Phys.Rev.Lett.104:102301,2010
[15] D. d'Enterria, G.Kh. Eyyubova, V.L. Korotkikh, I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva, A.M. Snigirev, Eur. Phys. J. C 66, 173 (2010)
[16] S. K. Prasad, Victor Roy, S. Chattopadhyay, A. K. Chaudhuri, Phys.Rev.C82:024909,2010
[17] G. Ortona, G. S. Denicol, Ph. Mota, T. Kodama, arXiv:0911.5158
[18] Y.Hama, T.Kodama and O.Socolowski Jr. Braz. J. Phys. 35 (2005) 24
[19] L. Cunqueiro, J. Dias de Deus, C. Pajares, Eur. Phys. J. C65:423-426, 2010.
[20] H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog and K. Werner, Phys. Rept. 350, 93, 2001
[21] L.D. McLerran, R. Venugopalan, Phys. Rev. D 49, 2233 (1994). ibid. D49, 3352 (1994); D 50, 2225 (1994)
[22] ALICE collaboration, Aamodt et al., arXiv:1004.3514
[23] CMS Collaboration, V. Khachatryan et al., arXiv:1005.3299